Sidelobe Manipulation using Butler Matrix for 60 GHz Physical Layer Secure Wireless Communication

Abstract-A means for scrambling the digital modulation content in the sidelobe of a wireless communication from a steerable antenna array is described. By exploiting the beam orthogonality characteristics associated with a Butler matrix, the concept of sidelobe manipulation is proposed. The method uses a Butler matrix parallel excited by an RF information data stream and artificial interference. The proposed system is implemented using a four by four Butler matrix MMIC and its operational characteristics are validated by bit error rate (BER) simulations for a 60 GHz QPSK transmission. The proposed architecture presented should find application in enhanced communication systems where security is of great concern.

Comments on the PPT

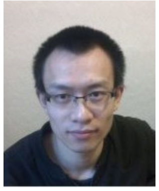
The slides 2-3 describe the characteristic of beam orthogonality in a Butler matrix driven antenna array.

With the benefit of the beam orthogonality property, the arrangement of a system with sidelobe manipulation capability using a Buter matrix was proposed in slide 4.

System performance simulation results presented in slides 5 and 6, in terms of the far-field patterns and constellation diagrams in IQ space, was performed under various scenarios, including different interference configurations and different receiver functionalities.

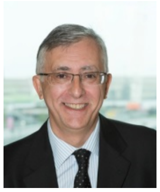
The experimental validation based on a four by four Butler matrix designed for V-band operation via 0.35 µm SiGe bipolar process are provided in slides 7-9. From the bit error rate (BER) results we can observe that the randomly updated interference reduces the probability of decoding by both standard and advanced receivers along unselected directions, and thereby enhancing physical layer secrecy performance, with regards to BER beam-widths and maximum sidelobe levels.

Author Bio



Yuan Ding received his Bachelor's degree from Beihang University (BUAA), Beijing, China, in 2004 and received his Master's degree from Tsinghua University, Beijing, China, in 2007, both in Electronic Engineering.

He was a RF engineer in Motorola R&D center (Beijing, China) from 2007 to 2009, before joining Freescale semiconductor Inc. (Beijing, China) as a RF field application engineer, responsible for high power base-station amplifier design, from 2009 to 2011. He is currently working toward his Ph.D. degree at the ECIT institute, Queen's University of Belfast, Belfast, United Kingdom. His research interests are in antenna array and physical layer security. He was the recipient of the IET Best Student Paper award at LAPC 2013.



Vincent F. Fusco (S'82–M'82–SM'96–F'04) received the Bachelor's degree (1st class honors) in electrical and electronic engineering, the Ph.D. degree in microwave electronics, and the D.Sc. degree, for his work on advanced front end architectures with enhanced functionality, from The Queens University of Belfast (QUB), Belfast, Northern Ireland, in 1979, 1982, and 2000, respectively.

He holds a personal chair in High Frequency Electronic Engineering at Queens University of Belfast (QUB). His research interests include active antenna and front-end MMIC techniques. He is head of the High Frequency Laboratories at QUB where he is also director of the International Centre for System on Chip for Advanced Microwireless. Professor Fusco has published over 350 scientific papers in major journals and in referred international conferences. He has authored two text books, holds patents related to self-tracking antennas and has contributed invited papers and book chapters.

Prof. Fusco serves on the technical programme committee for various international conferences including the European Microwave Conference. He is a Fellow of both the Institution of Engineering and Technology and the Institute of Electrical and Electronic Engineers. In addition he is a Fellow of the Royal Academy of Engineers and a member of the Royal Irish Academy. In 2012 he was awarded the IET Senior Achievement Award the Mountbatten Medal.

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Yuan Ding and Prof. Vincent Fusco

Beam orthogonality in a Butler matrix driven antenna array

The output signal vector ***A*** of an *N* by *N* Butler matrix can be obtained by

$$\boldsymbol{A}=\begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_N \end{bmatrix}=\begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1N} \\ T_{21} & T_{22} & \cdots & T_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ T_{N1} & T_{N2} & \cdots & T_{NN} \end{bmatrix}\begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_N \end{bmatrix}=\boldsymbol{T}*\boldsymbol{B}$$

The excitation vector at the input ports of the Butler matrix

$$T_{mn}=\frac{1}{\sqrt{N}}\cdot e^{-j\frac{2\pi}{N}\left(m-\frac{N+1}{2}\right)\left(n-\frac{N+1}{2}\right)} \qquad \left(m,n=1,2,\cdots,N\right)$$

Assume a 1-D half wavelength spaced antenna array with isotropic element radiation pattern is connected at the output of the Butler matrix, the far-field pattern for excitation B_n at the n^{th} Butler matrix input port is

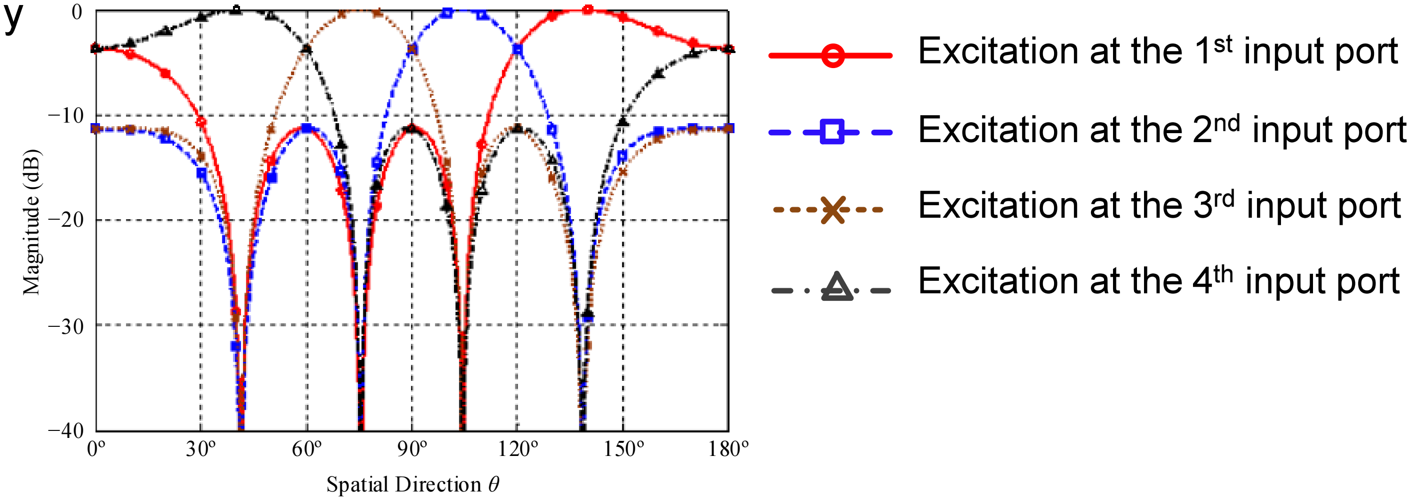
$$E_n\left(\theta\right)=\sum_{m=1}^{N}\left[\left(\frac{B_n}{\sqrt{N}}\cdot e^{-j\frac{2\pi}{N}\left(m-\frac{N+1}{2}\right)\left(n-\frac{N+1}{2}\right)}\right)\cdot e^{j\pi\left(m-\frac{N+1}{2}\right)\cdot cos\theta}\right]$$

Beam orthogonality in a Butler matrix driven antenna array

The main beam direction $\alpha_n = \arccos\left(\frac{2n - N - 1}{N}\right)$

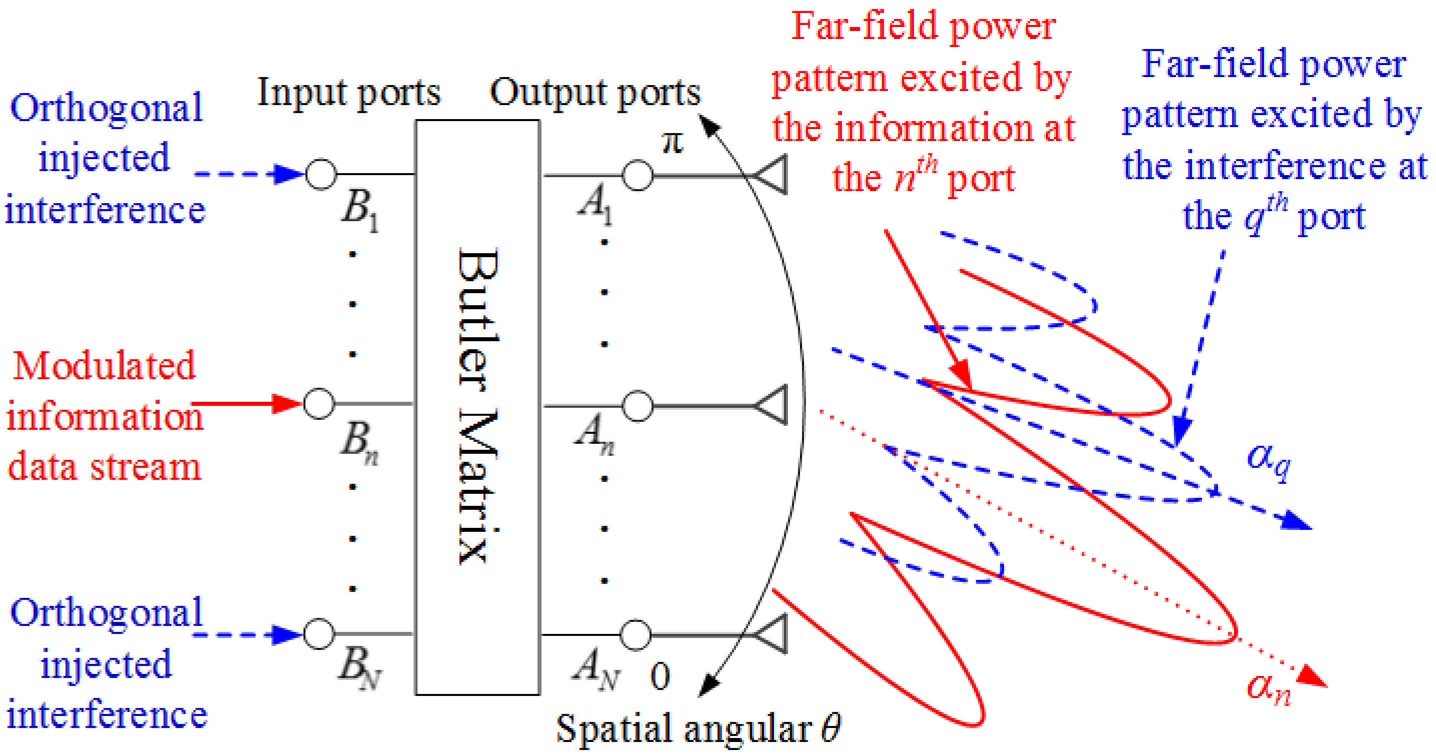
Similarly we can calculate $E_q(\theta)$ and α_q for the excitation B_q at the q^{th} Butler matrix input port.
We can verify that $E_n(\alpha_q) = 0$ when $n \neq q$, which indicates that the $E_q(\theta)$'s main beam is projected along the null radiation direction of $E_n(\theta)$. Ditto $E_n(\theta)$'s main beam and $E_q(\theta)$'s null direction.

Normalized radiation power patterns for each Butler matrix (4×4) input port excited separately



The maximum power spatial projection direction for each input port excitation is the power null when other ports are excited. This is, sometimes, termed orthogonality in the beam space.

The concept of sidelobe manipulation using a Butler matrix


Orthogonal injected interference
Input ports
Output ports
Far-field power pattern excited by the information at the n^{th} port
Far-field power pattern excited by the interference at the q^{th} port
π
B_1
A_1
Butler Matrix
Modulated information data stream
B_n
A_n
α_q
Orthogonal injected interference
B_N
A_N
0
α_n
Spatial angular θ

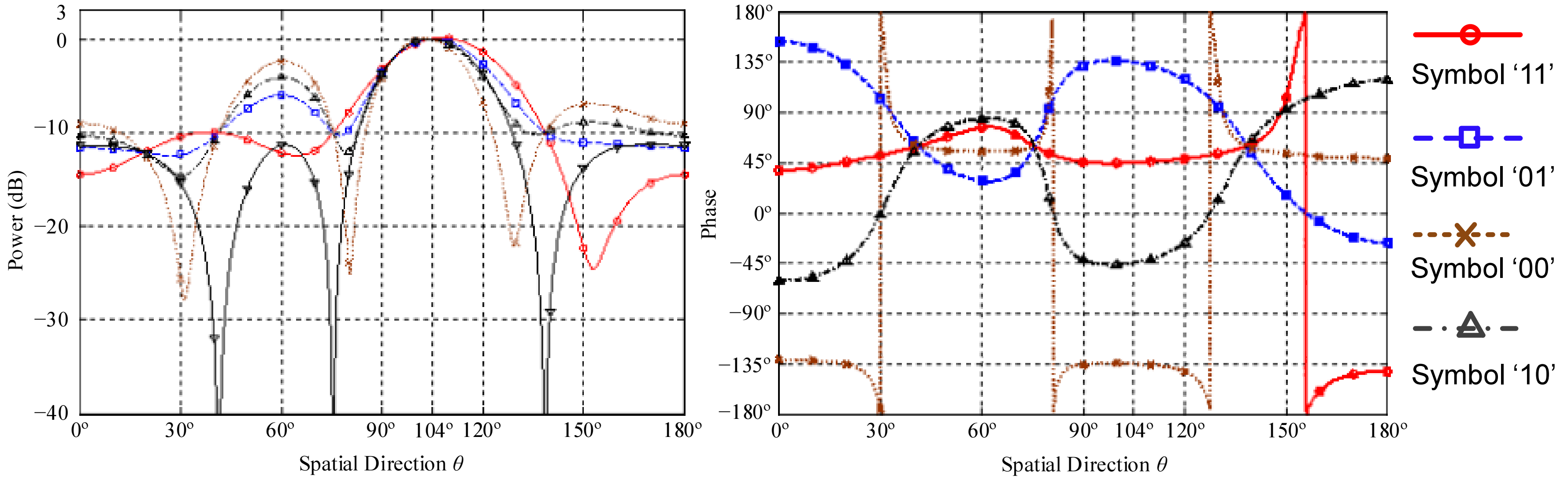
With the benefit of the beam orthogonality property, the interference signal is radiated with a null power direction along α_n, meaning that the information signal transmitted along this selected communication direction α_n is unaffected, while, simultaneously, the information leaked into other directions is submerged in multiplicative artificial interference.

Simulation results

Prerequisites:

- An ideal four by four Butler matrix with 1-D half wavelength spaced antenna array connected at the output ports.
- Each array element has an isotropic radiation pattern.
- An information data stream modulated with QPSK is injected into the Butler matrix at the second input port.
- The interference, injected into each remaining input port, is identical, and has a constant magnitude of 10 dB lower than that of the information signal.

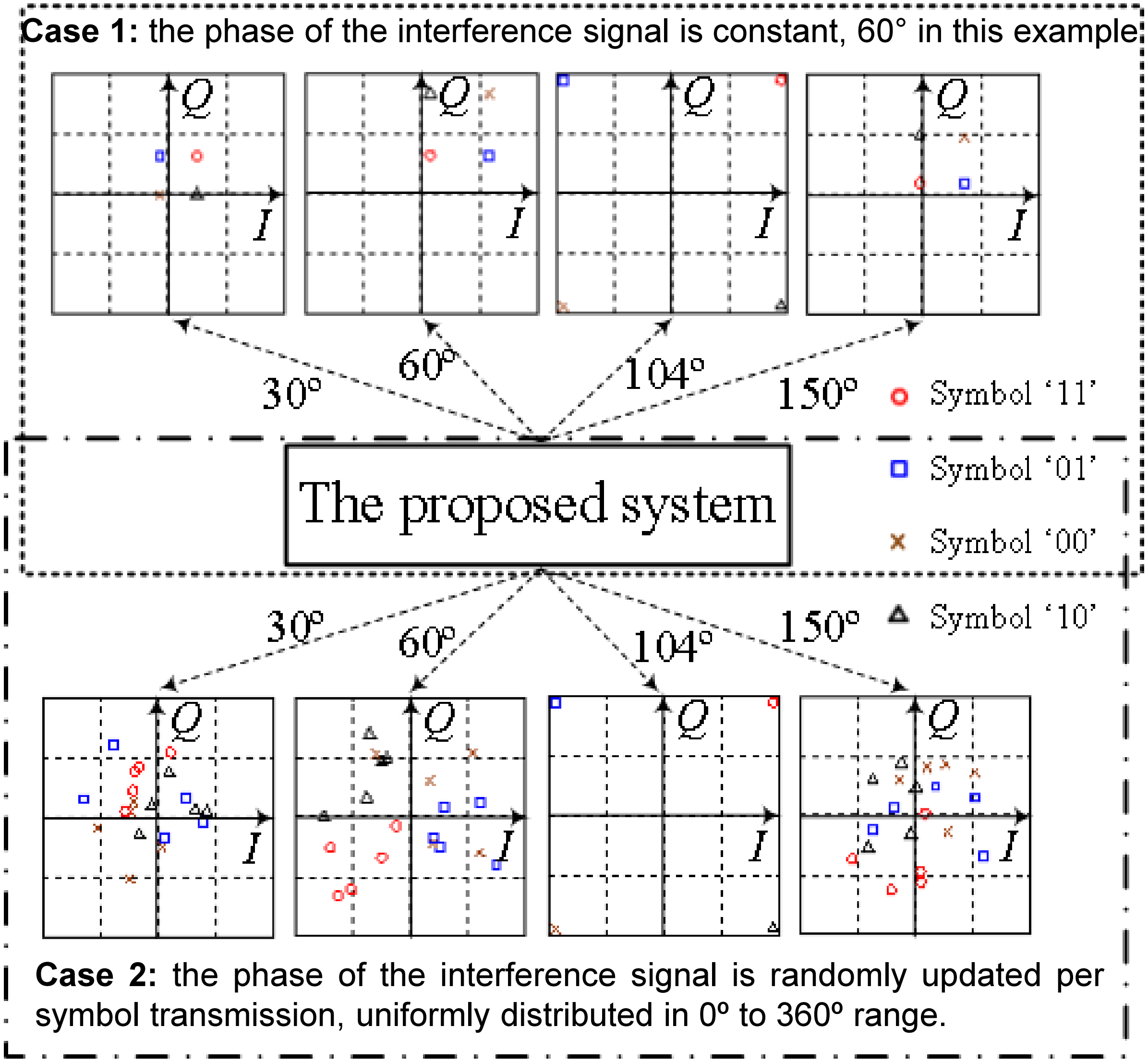
When the phase of the injected interference is constant, for example 60°, the far-field patterns for each QPSK symbol transmitted are shown,



Simulation results

The injected interference with a constant phase can only shift the constellation pattern in the IQ space as a whole along the all directions other than the selected direction, 104° in this example.

The injected interference with randomly updated phases can more effectively scramble the constellation points in IQ space, leaving the signal format in the desired direction intact.



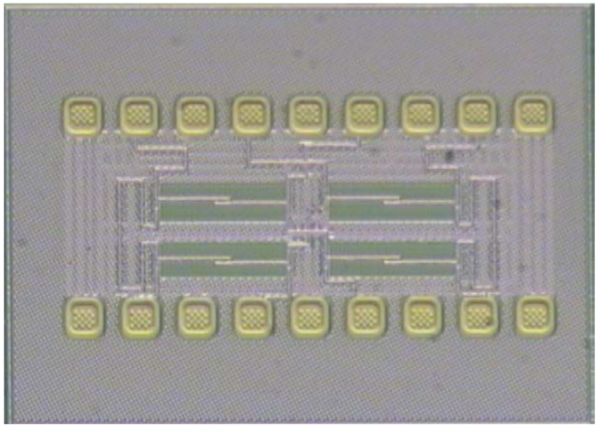
Case 1: the phase of the interference signal is constant, 60° in this example

Case 2: the phase of the interference signal is randomly updated per symbol transmission, uniformly distributed in 0º to 360º range.

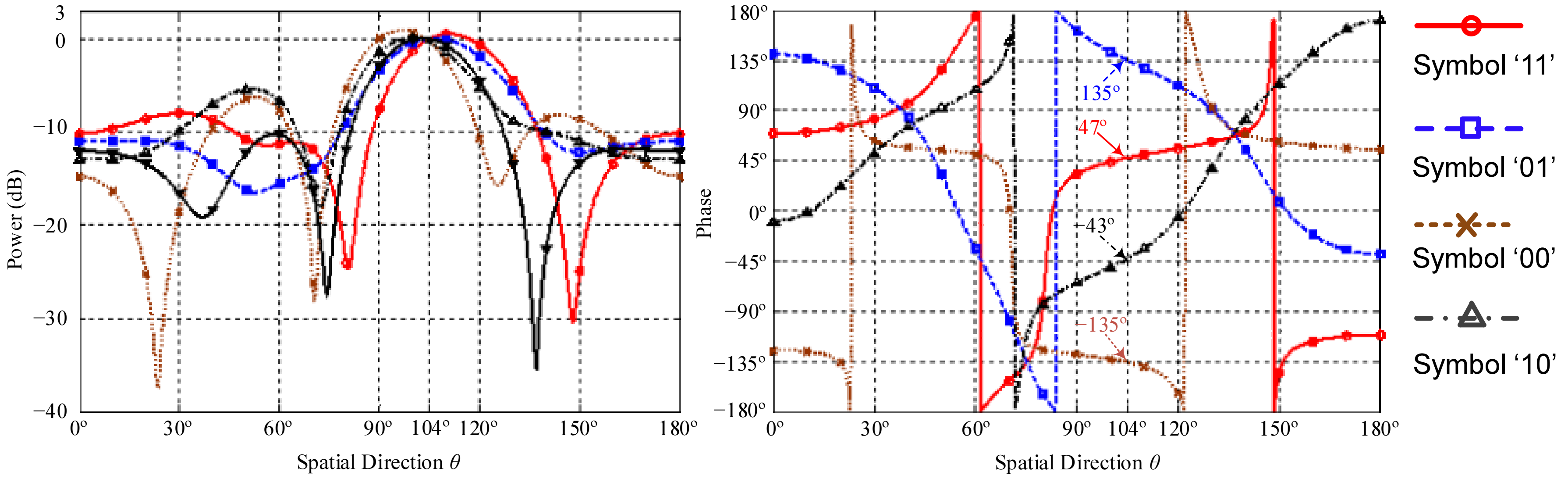
Q
I
30º
60º
104º
150º
The proposed system
○ Symbol '11'
□ Symbol '01'
× Symbol '00'
△ Symbol '10'

Experimental validation at 60 GHz

The proposed system was validated using a four by four Butler matrix designed for V-band operation via 0.35 *μm SiGe* bipolar process.



Based on the measured S-parameters of the Butler matrix, when the phase of the injected interference is constant, for example 60°, the far-field patterns for each QPSK symbol transmitted are shown,



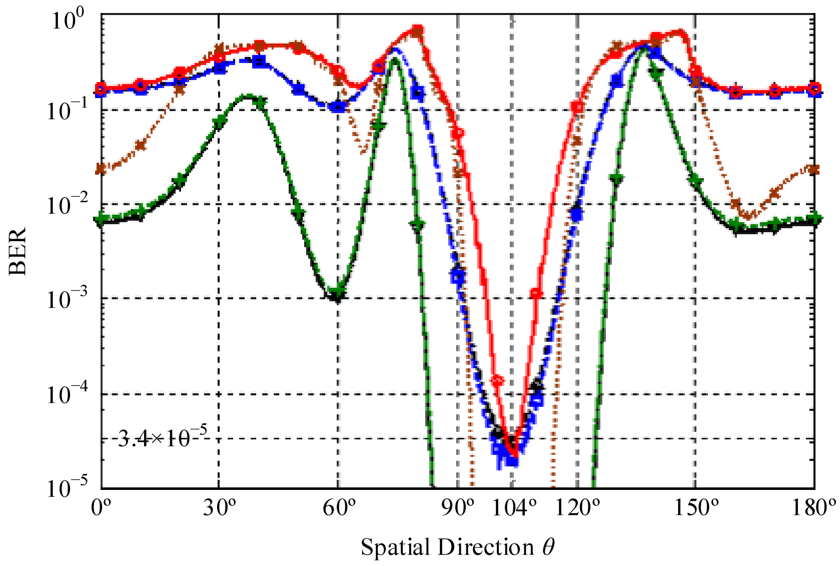
Experimental validation at 60 GHz

BER calculations:

Standard QPSK receiver (QPSK): it decodes received noisy symbols based on which quadrant the constellation points locate into.

More advanced receiver (APSK): it is able to detect the absolute magnitude and phase of each received symbol. The advanced receiver allows ‘minimum Euclidean distance decoding’.

A data stream with 10^6 random QPSK symbols is used, which allows BER down to 10^{-5} to be calculated

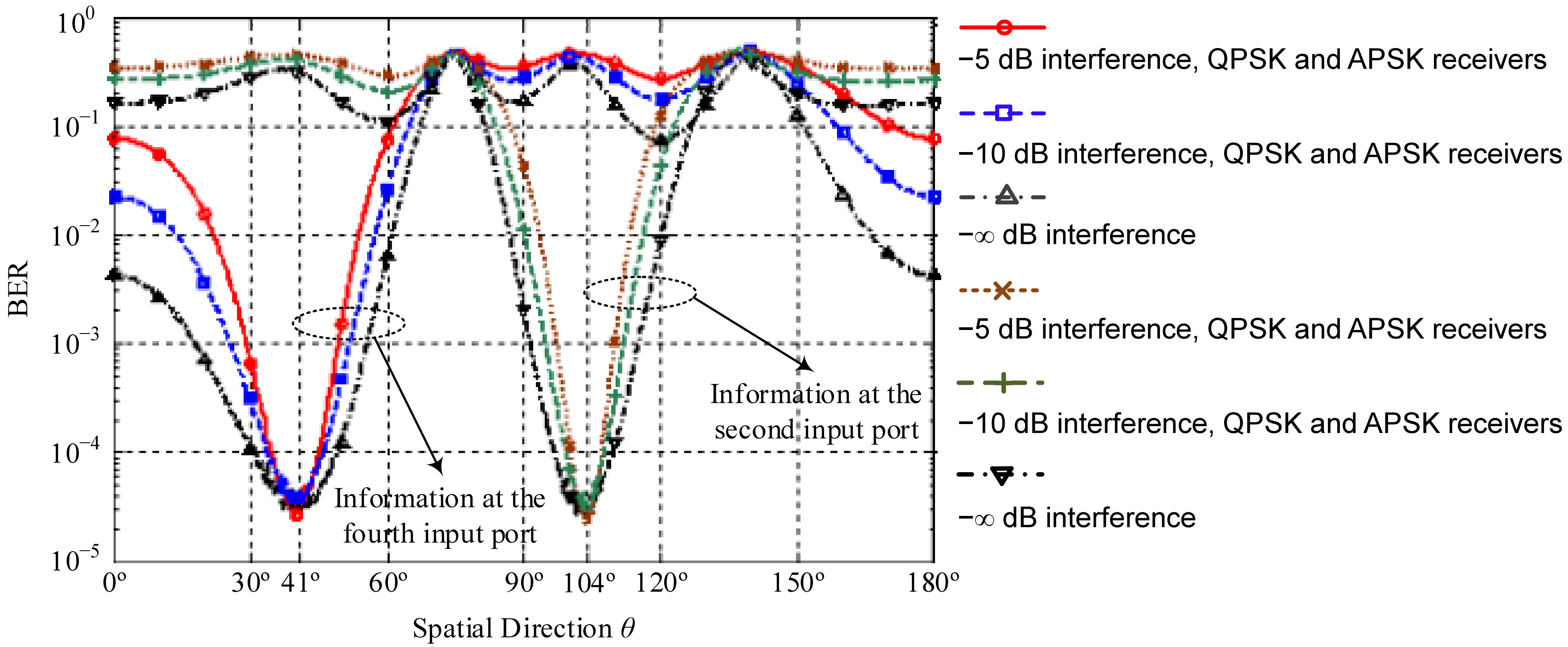


Information signal at the second input port and interference at each remaining input ports. The phase of the interference is kept constant, 60º.

Experimental validation at 60 GHz

BER calculations:

BER spatial distributions for information signal at the second or the fourth input port and interference at each remaining input ports. The phase of the interference is updated randomly. SNR along information beam directions is set to 12 dB



Conclusion

By employing Butler matrix, a means for distorting the digital modulation content in the sidelobes of a wireless communication was presented. Injected artificial interference is projected along all spatial directions other than the main information direction, and hence contaminates the leaked information in such a fashion to prevent eavesdroppers from information recovery through interception. It is also shown by extensive BER simulations, based on the measured S-parameters of a Butler matrix MMIC operating at 60 GHz, that dynamic random interference updating is highly effective at returning high BER along unselected communication directions. The approach suggested here opens the way for a new means for securing Gigabit per second data transmissions associated with V-Band short range communications while preserving beam steering. The method is generally applicable to any radio communication systems applying an orthogonal beam forming network.